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Techno-economic review of existing and new pumped hydro energy storage plant

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ABSTRACT

There has been a renewed commercial and technical interest in pumped hydro energy storage (PHES) recently with the advent of increased variable renewable energy generation and the development of liberalized electricity markets. During the next 8 years over 7 GW of PHES capacity will be added to the European network while projects are also planned in the USA and Japan. This paper provides a review of existing and proposed PHES plant and discusses the technical and economic drivers for these developments. Current trends for new PHES development generally show that developers operating in liberalized markets are tending to repower, enhance projects or build 'pump-back' PHES rather than traditional 'pure pumped storage'. Capital costs per kW for proposed PHES in the review region range between €470/kW and €2170/kW, however these costs are highly site and project specific. An emergence has also been observed in recent PHES developments of the use of variable speed technology. This technology, while incurring slightly higher capital costs, offers a greater range of operational flexibility and efficiency over conventional PHES. This paper has primarily been prompted by a lack of detailed information on PHES facilities worldwide and reviews current developments in the context of market and generation mix changes. The most recent large scale review of PHES faculties was undertaken by the American Society of Civil Engineers Hydro Power Task Committee on Pumped Storage in 1996. In the absence of data in the literature on new PHES plant development, this review draws primarily on publicly available information from utilities, government bodies and electricity regulators. In the same context this study is limited to a review region of the European Union, Japan and the United States as information on developments outside these areas is difficult to procure. This paper also gives a review of locations and proposed timelines for new PHES development and provides a thorough up-to-date overview of the development trends of this technology.

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1. Introduction

PHES is currently the only commercially proven large scale (>100 MW) energy storage technology with over 300 plants installed worldwide with a total installed capacity of over 95 GW [1]. In recent years there has been a flurry of interest in the technology resulting in the planning and building of a number of new plants in Europe and Japan. As of 2009, the European Union has an installed PHES capacity of 36 GW accounting for 4.3% of total generating capacity within the region. USA has an installed capacity of 21.8 GW with over 39 PHES plants and Japan with 34 plants (Plant with installed MW capacity >200 MW) has an installed capacity of 24.5 GW. While PHES was previously developed in many countries to facilitate the integration of large baseload generation, there has been a recent renewed interest in the technology with an increase of variable renewable generation such as wind in many countries. This paper examines the drivers and costs behind both new PHES development and existing developments. The majority of information gathered on new PHES development for this review paper comes directly from developer websites as there is a gap in this information in academic literature.

This paper is structured as follows: Section 2 introduces the technology and basic concepts of PHES; Section 3 reviews existing developments in the review region and details the owners of large PHES plant; Section 4 gives a general overview of proposed PHES and looks at the drivers for these developments. A detailed description of each proposed project is given on a country by country basis. Section 5 reviews the capital cost of new and exiting plant while Section 6 concludes with some observations on current trends.

While there are a large number of PHES plants in planning or early development stages in countries like the USA, the authors limited this review to plants deemed to be likely or very likely to be built. The principal criteria used to make this assessment were (1) whether construction has commenced and (2) has the Environmental Assessment Stage of planning been completed.

2. Pumped hydro energy storage

2.1. Technology

The fundamental principle of PHES is to store electric energy in the form of hydraulic potential energy. Pumping typically takes place mainly during off-peak periods, when electricity demand is low and electricity prices are low. Generation takes place during peak periods, when electricity system demand is high. Pumping and generating generally follow a daily cycle but weekly or even seasonal cycling is also possible with larger PHES plant.

The US Army Corps of Engineers distinguishes between two types of PHES [2] namely pure PHES and pump-back PHES. Pure PHES plants rely entirely on water that has been pumped to an upper reservoir from a lower reservoir, a river or the sea. Pure PHES are also known as 'closed-loop' or 'off-stream'. Pump-back PHES use a combination of pumped water and natural inflow to produce power/energy similar to a conventional hydroelectric power plant. Pump-back PHES may be located on rivers or valleys with glacial or hydro inflow. Fig. 1 shows a schematic of both Pure and Pump-back PHES.

The benefits of PHES to electrical system operations are well documented in textbooks and journals [3–7]. Its flexible generation can provide both up and down regulation in the power system while its quick start capabilities make it suitable for black starts and provision of spinning and standing reserve. A summary review of the operational characteristic of PHES in comparison to conventional power plant is provided in Table 1. In terms of operational characteristics and flexibility it is clear that gas turbine peaking plant such as OCGTs (open cycle gas turbine) offer some similar power system operation services, however generally at a higher capital cost. It would be interesting and useful to compare in detail the performance and benefits of PHES with those of OCGT and indeed other plant types. The purpose of this paper however is to provide a detailed review of PHES. The analysis provided in this paper could inform such a comparison.

3. Traditional development of PHES

PHES is a resource driven facility which requires very specific site conditions to make a project viable, i.e. high head, favourable topography, good geotechnical conditions, access to the electricity transmission networks and water availability. The most essential of these criteria is availability of locations with a difference in elevation and access to water. Some of the earliest PHES plants were built in the Alpine regions of Switzerland and Austria, regions that have a rich hydro resource and a natural complimentary topography for PHES. Prior to the emergence of liberalized

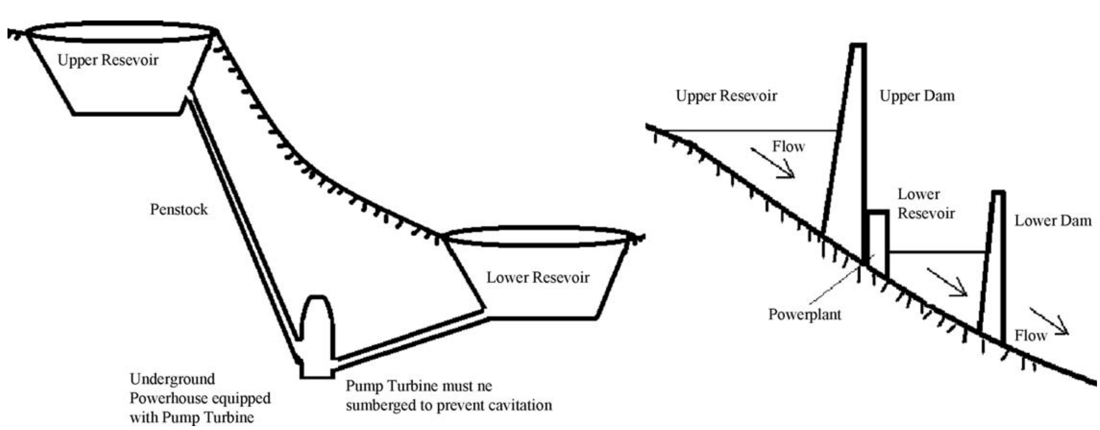

Fig. 1. Pure PHES on left and pump-back PHES on right.

Table 1
Typical operating characteristic of generating plant [7].

	Nuclear power plant	Coal fired plant	Oil fired plant	Gas turbine-peaker	PHES
Normal duty cycle	Baseload	Baseload	Baseload-midmerit	Peak load	Peak-midmerit
Unit start up-daily	No	No	Yes, hot	Yes	Yes
Load following	No	Yes	Yes	Yes	Yes
Quick start (10 min)	No	No	No	Yes	Yes
Frequency regulation	No	Yes	Yes	No	Yes
Black Start	No	No	No	Yes	Yes

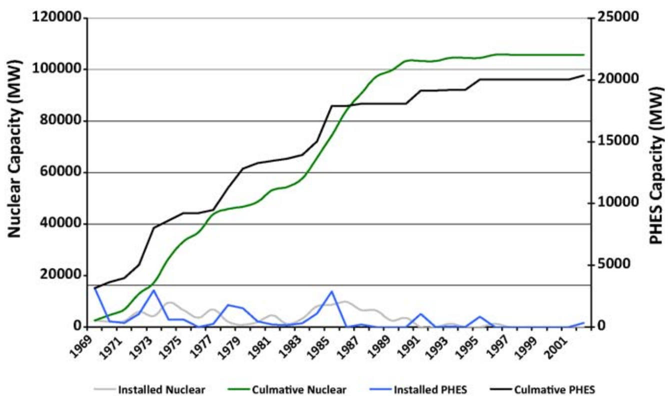

Fig. 2. Development of nuclear power and pumped hydro energy storage in USA [8].

electricity markets, PHES plants were built by state owned utilities as a system tool to supply energy in times of high demand and allow baseload power plants to operate at high efficiencies in periods of low demand. PHES also provided for such power systems management tasks as balancing, frequency stability and black starts. PHES plants have been built in many countries such as the USA and Japan to act as fast response peaking plant to complement high inertia nuclear power plants, but more recently there has been a renewed interest in the technology as an integrator for variable wind power. Fig. 2 shows that the development of PHES plants in the USA is strongly correlated to the development of nuclear power plants. PHES development on a European level is also closely correlated to nuclear development however countries such as Austria with no nuclear generation, but a rich hydro resource developed PHES to primarily enhance the operation and efficiency of large scale hydro power plants.

The chronological development of PHES in many countries shows the majority of plants were build from 1960s to the late 1980s. This was in part due to a rush for energy security and nuclear energy after the oil crises in the early 1970s. Fewer facilities were developed during the 1990s; due to a natural saturation of the best available (most cost effective) locations and a decline in growth in nuclear development. Fig. 3, with information gathered from individual plant developers, shows the development of PHES in Europe confirming the high level of construction in the 1960s through to the 1980s. Since the year 2000 however, a number of large PHES plant have come online in Europe, such as Goldisthal in Germany with a capacity of 1060 MW and Kopswerk II with a capacity of 450 MW in Austria.

As shown in Table 2, PHES generally accounts for a small percentage of a country's generation portfolio in terms of installed capacity. The country with the highest percentage of installed PHES worldwide is Luxemburg with 67%. Excluding Luxemburg the average installed capacity for the countries in the review region is approximately 6%. Countries with high installed capacities of PHES generally have a large amount of installed nuclear power capacity, like Latvia, Japan and the Slovak Republic or a rich hydro topography such as Croatia and Austria.

On the worldwide scale the USA and Japan have the highest installed capacities of PHES. The USA has an installed capacity of 21,886 MW [8] of pumped hydro energy storage plants accounting for 2.1% of total installed generating capacity. 39 PHES plants are currently in operation with installed capacities ranging from 8 MW to over 2000 MW. The largest plant is the Virginia Electric & Power Co. (now called Dominion) owned Bath plant with a capacity of 2862 MW built in 1985. The 1050-MW Helms pumped storage

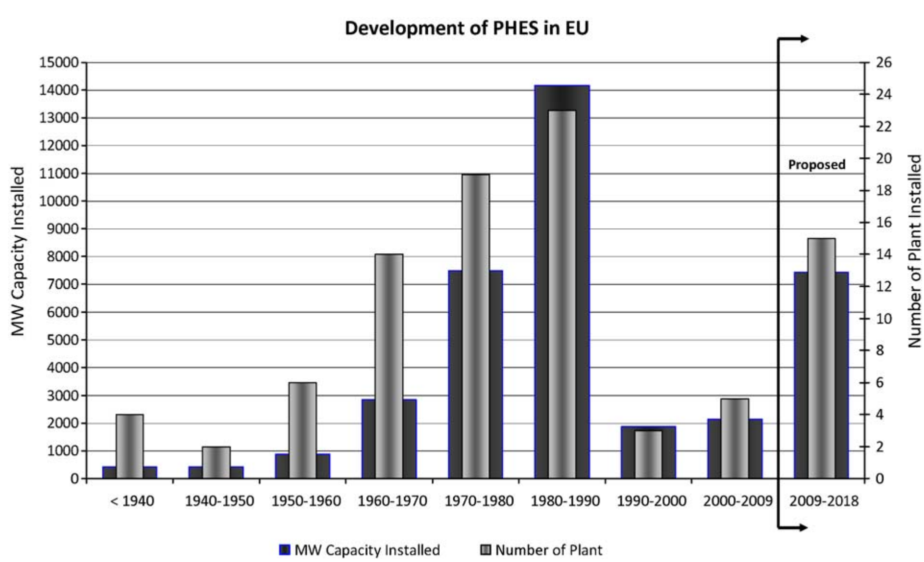

Fig. 3. Chronological development of PHES in MW capacity and plant number in the EU for existing and proposed PHES.

Table 2
Installed Generation Capacities (MW) in EU Member States (2006) [15] Japan (2008) [10] and USA (2007) [8]. PHES as a % of full installed capacity is also shown.

Country	Conventional thermal	Nuclear	Wind	Geothermal	PHES	Conventional hydro	PHES as % of total mix
Sweden	7882	9454	516	0	36	16,234	0.1
Croatia	1802	0	17	0	256	1804	6.6
Ireland	5171	0	746	0	292	234	4.5
Greece	9682	0	749	0	699	2436	5.2
Latvia	2471	1183	31	0	760	117	16.7
Bulgaria	6418	2722	27	0	864	1984	7.2
Slovak Republic	3051	2640	5	0	916	1598	11.2
Portugal	7685	0	1681	25	1048	4017	7.2
Luxemburg	463	0	35	0	1100	40	67.2
Czech Republic	11,528	3760	44	0	1147	1028	6.6
Belgium	8807	5825	212	0	1307	107	8.0
Poland	29,857	0	172	0	1406	925	4.3
Switzerland	844	3220	12	0	1655	13,355	8.7
United Kingdom	64,568	10,969	1955	0	2726	1514	3.3
Austria	6344	0	969	0	3580	8273	18.7
Italy	65,492	0	1902	671	4017	17,055	4.5
France	25,672	63,260	1412	0	4303	20,822	3.7
Germany	75,176	20,208	20,622	0	4854	4141	3.9
Spain	43,659	7365	11,736	0	5347	12,967	6.6
USA	776,122	100,266	16,515	2214	21886	77,885	2.2
Japan	142,000	49,470	1880	520	24575	21,465	10.2

project, operated by Pacific Gas and Electric Company in Fresno County, California with a head of 543 m has the highest head in the United States. The largest federally owned pumped storage project is the Tennessee Valley Authority's 1530 MW Raccoon Mountain project on the Tennessee River in Tennessee [9]. Major pumped storage plants (plants with installed capacity >100 MW) in the USA are characterised by a mixture of pure pumped storage (17 plants), operating on daily cycles and pump-back facilities (12 plants) with large energy storage capacity operating on weekly or seasonal cycles. A number of pump-back facilities, such as Castaic (1275 MW) also serve as part of irrigation and water regulation schemes. The average size of a PHES plant in the United States is 520 MW. The majority of PHES plants were built in the period 1970–1980 when 14 facilities totalling a MW capacity of 9636 MW were installed.

Like the USA, Japan developed PHES to compliment nuclear power facilities, providing peak power in the evenings and pumping when demand is low. Japan has the third largest installation of nuclear power worldwide with a total of 53 units accounting for 47.9 GW installed capacity. Currently Japan has 34 PHES major plants with a total capacity of 24,575 MW [10]. Current installed capacities in Japan range from 200 MW to 1932 MW. The majority of plants are pure pumped hydro storage schemes operating on a daily cycle characterised by large MW capacity and relatively short storage times, typically 5–10 h. PHES installations account for 10.2% of full installed generating capacity.

In a European context the majority of PHES facilities are concentrated in the Alpine regions of France, Switzerland and Austria however Germany has the largest number of PHES plants with 23 operational plants ranging in capacity from 62.5 to 1060 MW. Germany is second only to Spain in terms of installed MW capacity. Over 6000 MW of PHES is installed on the Iberian Peninsula. Spain has 14 PHES plants with sizes ranging from 65 to 745 MW. The largest plant currently in operation is the Iberdrola owned *Villarino* plant with a capacity of 745 MW. Portugal has five major PHES plants with an average capacity of 160 MW. PHES in Portugal and Spain are predominantly pump-back type operating on major rivers or operating as part of larger hydro complexes or cascades. This type of facility can also play a number of important roles from irrigation to flood control. The largest PHES plant in the EU is the 1800 MW EDF owned '*Grand Maison*' facility in the French Alps opened in 1987. The 1728 MW Dinorwig plant in the UK was previously the largest PHES plant in Europe. Dinorwig can achieve full load from spinning in less than 20 s [11].

3.1. Ownership of current PHES

While many PHES facilities were built before liberalized markets by State owned utilities, more recent times has been characterised by mergers and buy-outs of competing private companies. Table 3 details the current ownership of PHES in the review region. The largest owner of individual PHES plant in the review region is Iberdrola [12] with a total of 10 operational plants in Spain and Portugal. TEPCO [13] and J-Power [14] (also know as EPDC) are the largest owners of plant MW with a combined capacity of over 11,700 MW. EDF are the largest owner and operator of PHES plant in Europe on a MW basic. In the USA there is no clear major owner of PHES with the majority of the 34 plants being individually owned. The largest owner of PHES is the US Bureau of Reclamation with 4 plants totalling to an installed capacity of 340 MW. The California Department of Water Resources owns three plants with a total installed capacity of 800 MW.

4. New developments

4.1. Technology developments

While PHES is a relatively mature and established technology a number of recent innovations and improvements have been observed.

Table 3
Majors owners of PHES in the review region[a].

Owner	Number of operational plants (2009)	Approximate pumping capacity (MW)
Iberdrola	10	3327
TEPCO	9	6801
Vattenfall	8	2893
J-Power	7	4970
EDP	6	969
EDF	6	4978
Verbund	6	1182
Endesa	5	1577
E-on Wasserkraft	5	1009
Schluchseewerk AG	5	1740

[a] Values are obtained from web sites of individual companies.

A number of proposed PHES plant (*Linthal 2015* and *Nant de Drance*) will use variable speed pump/turbine units. This technology is already employed in a number of existing PHES units in Japan. The advantage of variable speed pump/turbine units is the variable speed pumped storage plants use asynchronous motor-generators that allow the pump/turbine rotation speed to be adjusted. This technology allows regulation of the amount of energy absorbed in pumping mode. This facilitates energy storage when power levels available on the network are low and in addition to reducing the number of starts and stops can help regulate the network frequency or voltage in pumping mode [16]. This technology also allows turbines to operate closer to their optimal efficiency point. A study in the USA [17] has estimated that this would increase the power component cost of a variable speed plant as opposed to a conventional PHES plant from approximately $ 1000–1050/kW.

In the area of improved efficiencies the Kannagawa PHES plant in Japan was the first plant to employ a 'splitter runner' which is a multi-blade turbine pump runner. Improvements in power generation and pump efficiencies of up to 4% are reported for this runner by TEPCO [18].

In the area of site development, J-POWER became the first company in the world in 1999 to build and operate a 30 MW seawater PHES plant at Okinawa with a head of 136 m. Research for the plant development started in 1981 and focussed on corrosion preventive measures [19]. Seawater PHES may have several advantages over conventional PHES such as lower civil construction cost and greater site availability. See-water PHES technology has yet to develop a commercial track record however, with only one completed plant worldwide.

4.2. Drivers for new PHES development

From a review of available public literature, developers of new PHES cite a number of key reasons for new developments, these can be summarised as follows.

- Government and regional targets for increased renewable energy are stimulating wind energy development in many countries. Increased variable generation is seen to drive the demand for system reserve and increase the value of PHES in ancillary services.
- A general growing demand for energy and peak power in liberalized markets across Europe.
- Increased interconnection is cited as contributing to the value of PHES as developers have access to more potential markets and market opportunities.
- Security of supply. PHES is seen by many developers to contribute to a countries or regions security of supply.
- Reduce volatility or increase efficiency of current hydroelectric assets. Developers who already have existing hydroelectric or PHES assets are using newer more efficient equipment to increase the operational efficiency of existing plants.

Within the EU there is currently approximately 7400 MW of new PHES development proposed, with a total investment cost of over €6 billion. This constitutes approximately 20% increase in installed capacity of PHES in the EU. Fig. 4 [15] shows existing and planned PHES in the EU as well as current installed wind capacity and the percentage of PHES of total system capacity. Switzerland has the highest amount of planned PHES at 2014 MW. Table 4 details proposed PHES in Europe. A review of new developments on a country by country basis is given in the next sections. Information for these developments was gathered from publically available information from project developers. Note that a number of proposed PHES projects which are in the early stages of development and have not completed environmental impact statements, such as Scottish and Southern Energy's two proposed PHES projects in Scotland [20] are not detailed here.

4.3. Switzerland

In a European comparison, Switzerland is fourth in terms of contribution of hydropower towards electricity production, behind

Table 4
Proposed PHES in Europe.

Country	Proposed PHES (MW)
Switzerland (CH)	2140
Portugal (PT)	1956
Austria (AT)	1430
Germany (DE)	1000
Spain (ES)	720
Slovenia (SL)	180
Total	7426

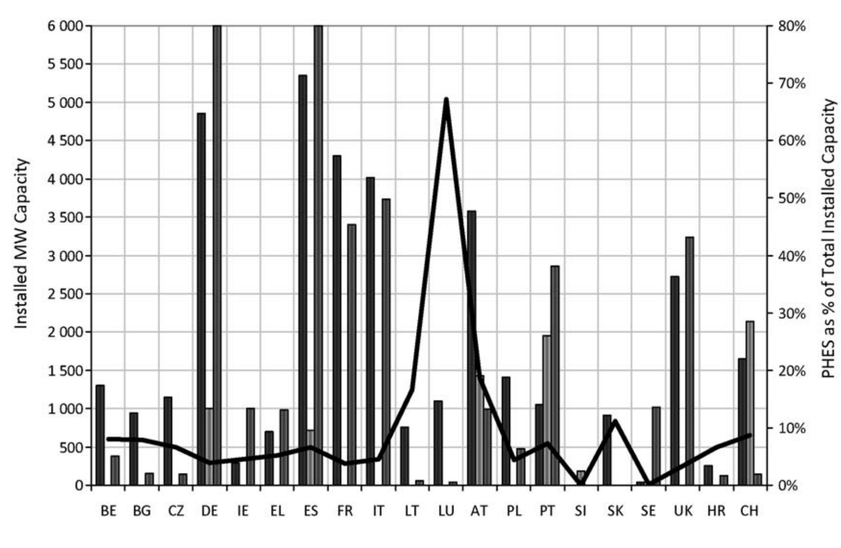

Fig. 4. Installed PHES, proposed PHES, existing installed wind capacity and % of PHES of full installed capacity in the EU. *Note*: For illustration purposed Germany (DE) and Spain (ES) installed wind capacity is limited to 6000 MW. Actual installed wind capacity in Germany is 23,903 MW and 16,740 MW in Spain.

Table 5
Summary details of proposed PHES in Switzerland.

Proposed Plant	Capacity (MW)	Published cost	Project developer	Operational date
Linthal 2015 (NESTIL)	140	100 million Swiss francs	Axpo Group	2009–2010
Linthal 2015 (Linthal)	1000	1 billion Swiss francs	Axpo Group	2015
Nant de Drance	600	990 million Swiss francs	*Nant de Drance SA*	2015
KWO Plus (Gimsel 3)	400	320 million Swiss francs	Kraftwerke Oberhasli AG	2014

Norway, Austria and Iceland. Hydropower plays a major role in Switzerland's energy production with a share of around 57%. In Switzerland's hydropower plant statistics, a distinction is made between four types of plants: run-of-river (3667 MW), storage (8067 MW), pumped storage (1384 MW) and basic water flow plants (316 MW) [21]. A number of new PHES plants are planned here, with developers citing security of supply, increased wind penetration in European countries and an increase in demand in peak power in liberalized European markets as major incentives for development.

Axpo Group is developing the *Linthal 2015* PHES project which consists of two major expansion phases to the existing *Linth Limmer* complex [22]. The first phase *NESTIL* is a 140 MW pumping capacity and 110 MW turbine capacity plant that is being built into the existing complex. The construction of NESTIL began in 2005 and will take 4 years at an estimated cost of 100 million Swiss francs. The second phase *Linthal* is part of the same complex of reservoirs has a 1000 MW pump/turbine capacity. Construction of Linthal is expected to take 5 year and has an estimated cost of 1 billion francs.

Construction started in 2008 at the 600 MW *Nant de Drance* PHES plant. The project is being developed by *Nant de Drance SA* a consortium of three companies Alpiq, CFF and FMV. The facility will use existing reservoirs at the *Vieux Emosson* site. The project is expected to be completed in 2015 and cost of the project is estimated at 990 million Swiss francs [23].

Kraftwerke Oberhasli AG power company (KWO) is currently in the process of its 845 million Swiss franc investment and enhancement program (KWO Plus) of its existing hydroelectric facilities. This program includes the construction of the new 400 MW PHES *Gimsel 3* plant at a cost of 320 million Swiss francs. The plant will use existing reservoirs at the complex and compliment the existing 344 MW *Grimsel 2* PHES plant. Construction is expected to start on this facility in 2010 and end in 2014 [24]. Table 5 provides a summary of proposed PHES development and costs in Switzerland.

4.4. Portugal and Spain

In the European Union, Portugal is leading a resurgence in PHES with plans to build or upgrade up to 10 facilities adding approximately 2000 MW of PHES to its current capacity of 980 MW. Portugal has a total installed generating capacity of 14916 MW with a total hydroelectric installation of 4943 MW. Hydroelectric capacity factors for the past 5 years have been below average at 56% and Portugal is exposed to volatility in hydroelectric production. In 2008 Portugal's imported balance for electricity was 19% with hydro resources supplying 11% of electricity while in 2007 the import balance was 15% with hydro supplying 18% of electricity [25]. This volatility along with ambitious government renewable energy targets and a relatively under exploited hydro resource is stimulating a renewed commercial interest in PHES development. Portugal is one of the few European countries with significant hydro potential (54%) to be developed [26]. Portugal has ambitious renewable energy goals. By 2010, renewable energy should represent 45% of the total consumption in the country. The installed wind energy capacity is expected to increase to 5100 MW by 2010. In this context the Portuguese government commissioned '*Plano Nacional de Barragens de Elevado Potencial Hidroelélictrico*-'The National Program of High Hydroelectric Potential Dams' [27] (PNBEPH) in 2007. The PNBEPH identified and defined priorities for investments in large hydroelectric developments in the project horizon 2007–2020. The PNBEPH intends to reach a national hydro rated capacity above 7000 MW in 2020 (70% of the national hydro potential). Particular emphasis was given in the PNBEPH to hydroelectric plants with pumping capacity given its ability to facilitate the integration of variable renewable generation. Wind power production and electricity demand in Portugal are highly uncorrelated with the windiest periods occurring at night time and early morning. Preliminary analysis within the PNBEPH indicated the ideal relationship between pumping capacity and wind power was in the order of 1.0 MW pumping capacity to 3.5 MW of wind power.

One of the largest new PHES plants to be built in Portugal (and Europe) is the *Alto Támega* complex [28]. This project is being built by the Spanish utility Iberdrola. This complex comprises of four dams (*Daivoes, Gouaves, Padroselos, Alto Támega*) with a total generating capacity of 1200 MW and a total pumping capacity of 900 MW. The company also recently won a tender to manage the existing *Aguieira* PHES plant (336 generating capacity and 270 pumping capacity) in Portugal until 2014 [29]. Iberdrola are also developing and expanding a similar complex in Spain at the *La Muela* complex which when completed in 2012 will have a total generating capacity of 1710 MW and 1260 MW of pumping capacity. EDP (Energias de Portugal) are building four new PHES plants in Portugal namely; *Baixo Sabor*, *Foz Tua* and *Fridão/Alvito* and expanding *Alqeueva II*. EDP state that increased wind penetration is adding to the value of PHES through energy storage and ancillary services and making it attractive for investment. Increased interconnection with Spain (set to double to approximately 3 GW by 2014) and the liberalized Iberian electricity market (MIBEL) are also increasing the attractiveness of PHES for utilities and investors in Portugal [30]. Table 6 provides a summary of costs and MW capacities of proposed PHES in Spain and Portugal.

Table 6
Summary details of proposed PHES in Portugal and Spain.

Facility	Size	Published cost	Developer	Operational date
Alto Támega Complex	1200 MW turbine, capacity 900 MW pumping capacity	1.7 billion Euros [28]	Iberdrola	2018
Baixo Sabor	170 MW	369 million Euro [31]	EDP	2013
Foz Tua	324 MW	340 million Euro [32]	EDP	2018
Fridão/Alvito[a]	256 MW + 136 MW	510 million Euro [33]	EDP	2016
Alqeueva II (expansion)	240 MW	150 million Euro [34]	EDP	2012
La Muela II (extension)	720 MW	350 million Euro [35]	Iberdrola	2012

[a] Subject to the confirmation by INAG (the Portuguese Water Institute).

4.5. Austria

Hydroelectric power supplies approximately 55% of Austrian electricity [36] with an installed capacity of 11,853 MW of which 3.5 GW is PHES. Austria has 13 major PHES plants with the earliest plant, *Rodundwerk I* (198 MW) coming into full operation in 1952. The majority of PHES in Austria are situated in the west and south of the country in the Alpine regions. PHES in Austria, (as in the alpine regions of Switzerland) is characterised by large storage reservoirs with some glacial inflow and are generally connected by long underground penstocks into multi-stage hydroelectric complexes such as the Malta or Kaprun complexes. Major owners of PHES in Austria are the utilities Verbund, Illwerke and Tiroler.

Liberalization of electricity markets, the rapid development of wind energy and increased electricity demand are cited as the main drivers for increased PHES development in Austria. In November 2008 the Vorarlberger Illwerke AG KOPS II (Kopswerk) plant went into operation. KOPS II is located at the site of the existing KOPS plant. The project uses existing reservoirs and has a head of approximately 800 m. The project cost approximately €360 million and took 3.5 years to build. Plant KOPS II has a full range of controllability of $\pm$100% in turbine operation and in pump mode using hydraulic short circuit [37]. Following the commissioning of KOPS II, Vorarlberger Illwerke has 1700 MW of turbine output and 980 MW of pump capacity in the Austrian market [38].

Verbund are planning to build two new PHES Plant – *Reißeck II* and *Limberg II*. Verbund currently own and operate 6 PHES plants with a total pumping capacity of 1182 MW and generating capacity of 1621 MW [39]. *Limberg II* (480 MW capacity with a head of 360 m) is being built into the Kaprun Power Storage Complex and is expected to be completed by 2012 at a cost of €365 million. After the start of operations of *Limberg II*, the turbine output of the Kaprun Power Storage Complex will increase from 353 to 833 MW. The power output in the pump operation is set to climb from 130 to 610 MW [40]. *Reißeck II* with a planned installed capacity of 430 MW and a head of 595 m is being added to the Malta complex in Carinthia. The project will use existing reservoirs and resources and is estimated to cost €335 million. The project is currently going through the environmental planning stage and is expected to be completed by 2014 [41].

Kelag are adding the 140 MW Feldsee PHES plant at a cost of €75 million to its Fragant hydro complex (334 MW) also in Carinthia. The new PHES plant will use existing reservoirs at a head of 532m. The project is expected to be completed by late 2009 [42]. A summary table of new Austrian PHES development is provided in Table 7.

4.6. Germany

Germany with 23 operational PHES plants has the highest number of plants in Europe. In 2003 after 30 years of planning and 7 years of construction, Germanys largest pumped storage plant *Goldisthal* in Thuringia was put into operation. The plant, owned by Vattenfall has an installed capacity of 1060 MW and a storage capacity of 8.5 GWh [43]. Currently one new PHES facility is planned for Germany. Schluchseewerk AG, owner of over 1600 MW of PHES in Germany are in the planning phase of the 1000 MW *Hornbergen II* project. This is an extension to the *Hotzenwaldgruppe* complex in southern Germany. The project is expected to be completed by 2014 and is estimated to cost over €700 million. Increase in wind energy installations, increase in energy demand in the region and electrical grid congestion from the north to the south of Germany are cited as prime reasons for development of the plant [44].

Table 7
Summary details of proposed PHES in Austria.

Facility	Size (MW)	Published cost	Developer	Operational date
Reißeck II	430	335 million Euro	Verbund	2014
Limberg II	480	365 million Euro	Verbund	2012
Feldsee	140	75 million Euro	Kelag	2009

4.7. Slovenia

Slovenia utility *Soške elektrarne Nova Gorica* (SENG) are in the final construction phase of the countries first PHES plant. The 520 m head 180 MW Avče PHES plant is estimated to cost SENG €91.4 million. SENG have secured loans from the European Investment Bank (EIB) for the construction of the project. The plant is scheduled to be completed at the end of 2009 [45].

4.8. USA

In the past 15 years just one major PHES plant (Rocky Mountain 848 MW) was built in the USA. The most recent PHES build in the USA is the 40 MW Lake Hodges project in San Diego [46]. Recent renewed commercial interest in PHES is evident with companies such as Brookfield Power Corporation, Nevada Hydro Company and Symbiotic LLC announcing pipelines of over 6000 MW of planned PHES plant [47]. At governmental level, Secretary of Energy Dr Steven Chu made positive comments [48] about the merits of PHES but has urged that new plants must not adversely affect local environment sensitivities and that lessons could be learned from European operators on this issue. According to official statistics from the Energy Information Administration there are currently no planned construction of PHES plants in the USA up to 2012 [49] however the Federal Energy Regulator Commission (FERC) has granted over 30 pre-permits[1] totalling over 22,000 MW of PHES. The majority of pre-permits were issued for potential locations in western USA states with high renewable portfolio standard targets, namely California (20% target by 2010), Washington (15% target by 2020), Nevada (20% target by 2015) and Oregon (25% target by 2025). A high number of pre-permit applications do not mean that projects will get build. Fifteen years ago the FERC had license applications for 18 GW of new pumped storage (42 plants with 31 in the west). However, deregulation, relatively cheap natural gas, and risk adverse private investors led nearly all developers to back out of construction [50]. Because of the need for significant elevation changes in pumped hydroelectric plan designs, the number of environmentally acceptable sites for future pumped hydroelectric facilities is very limited. Nevertheless, planning is underway to add new pumped hydro storage power plants to the USA grid [51]. As of 2009, one final Environmental Impact Statement has been submitted to the FERC for a pumped hydro scheme-The 500 MW (6000 MWh storage) Lake Elsinore Advanced Pumped Storage Project (LEAPS). The FERC has estimated the cost of the project (not including Transmission line) to be approximately US$ 1 billion [52]. A construction date has not yet been given for the project. A study undertaken for the ERPI in 1988 [7] identified a number of reasons why the utilities in the USA were reluctant to pursue PHES. These reasons ranged from the availability of suitable sites, long lead times for licensing by regulatory agencies (4–6 years) and cost overruns in a number of PHES projects.

[1] A preliminary permit, issued for up to 3 years, does not authorize construction; rather, it maintains priority of application for license (i.e., guaranteed first-to-file status) while the permittee studies the site and prepares to apply for a license. The permittee must submit periodic reports on the status of its studies. It is not necessary to obtain a permit in order to apply for or receive a license.

4.9. Japan

Although steady development of hydroelectric power plants is desired, Japan has used nearly all available sites for the construction of large scale hydroelectric facilities, and so recent developments have been on a smaller scale [10]. In Japans largest service area, the Tokyo Electric & Power Company (TEPCO) service area, the proportion of PHES as a percentage of the total capacity of the entire power network is determined based on a power network system analysis that aims to minimize the power generation cost of the entire power network taking into consideration the pattern of daily electricity usage. The current optimal proportion of PHES capacity as a percentage of the total capacity of the entire power network in TEPCO's service area is estimated to be 10–15% [53].

All PHES plants in Japan are owned and operated by the 10 privately owned regional electric power companies and J-Power who own 4.9 GW of PHES. A number of PHES plants are currently in the construction phase: Tokyo Electric & Power Company are currently in the construction phase of the *Kannagawa* plant which when completed in 2015 will be Japans largest PHES plant with an installed capacity of 2820 MW [54]. TEPCO also have the option to bring another 800 MW online at its *Kazunogawa II* plant to increase its capacity to 1600 MW. *Kazunogawa* PHES is unique in that it has one of the world's largest ultra high head large capacity turbines (400 MW pump with a head of over 700 m) [55]. Kyushu Electric Power Company are in phase II of the construction of the *Omarugawa* PHES, currently 300 MW are operational. The plant is expected to be completed by 2011 with a maximum capacity of 1200 MW [56]. Table 8 provides a summary of proposed PHES development in Japan.

5. Capital cost for PHES and current trends

PHES plants are characterised by long asset life (typically 50–100 years), high capital cost, low operation and maintenance cost and round-trip efficiencies of 70–75%. Project costs for PHES are very site specific with some quoted costs varying from of €600–3000/kW [57]. Furthermore capital costs depend not only on the installed power but also on the energy storage and MW capacity at any given site.

A study [7] undertaken by the EPRI of 14 PHES plant build in the USA from the years 1963 to 1985 found that build costs varied from under $ 300 to over $ 600/kW with an average cost of $ 434/kW. The costs presented in the study are in January 1988 currency and exclude interest during construction and transmission costs. Fig. 5 presents the costs detailed in the study. The study also noted that there was an observed increase in capital costs in "recent" builds in the USA (recent assumed to be 1980+). This increase in costs was attributed to higher licensing costs, higher cost in providing more efficient and reliable plant and construction delays due to technical and financial problems.

Fig. 6 details the published capital costs and installed capacities for all proposed PHES plants in the review region, the majority of which are in Europe. A general linear trend is observed in the relationship between installed capacity and capital cost. Capital costs per MW for proposed PHES in the review region are between €470/kW and €2170/kW. Unfortunately not enough consistent data was publically available to compare costs in terms of €/kWh. It must be borne in mind that the majority of projects in the review region are either extensions to existing projects, repowering of projects or pump-back PHES.

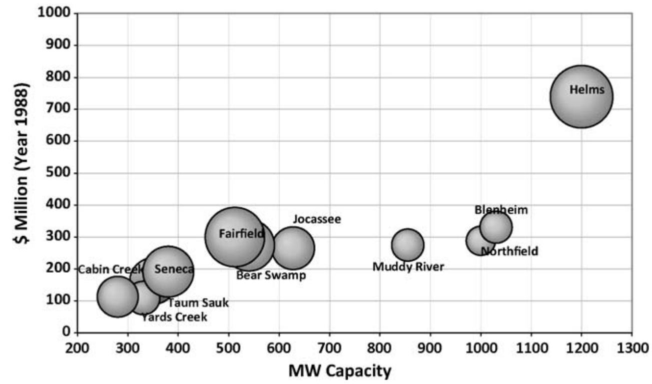

Fig. 5. MW capacity and capital cost (ex transmission line and interest during construction) for 14 PHES Plant in the USA built between 1963 and 1985. *Y*-axis is full CAPEX cost in US$ (1988). Size of bubble is indicative of relative cost per MW.

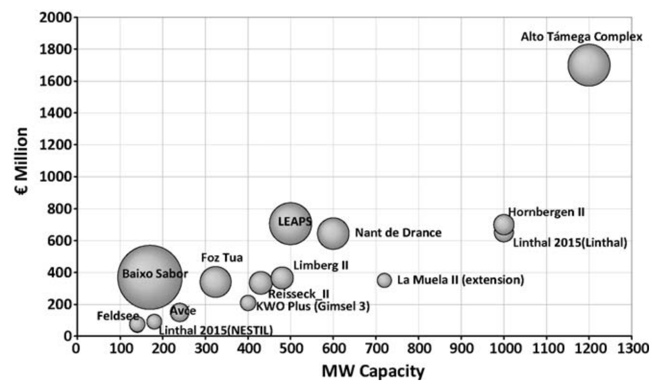

Fig. 6. MW capacity and capital cost (ex transmission line) for proposed PHES in review region. *Y*-axis is full CAPEX cost. Size of bubble is indicative of relative cost per MW. Plants in Switzerland and USA were converted to € using the following exchange rates. (1 CHF = €0.6515, 1 USD = €0.70715).

PHES projects may be remunerated in liberalized electricity markets through ancillary services payments, capacity payment and electricity trading. Generally electricity trading is the major source of revenue for PHES as operators may take advantage of energy arbitrage opportunities. For arbitrage pumping price has to be at least 25–30% lower than selling price to compensate for energy losses and significant volatility (not necessarily high energy prices) must be present in the wholesale price of electricity to make revenue. Increased wind generation in many countries can naturally lend itself to increased price volatility in the wholesale market [57].

Current trends for new PHES plants in Europe show that developers operating in liberalized markets are tending to repower, enhance projects or build 'pump-back' PHES rather than traditional 'pure pumped storage'. This is partly driven by a lack of economically attractive new sites. An advantage with

Table 8
Summary details of proposed PHES in Japan.

Facility	Installed MW capacity	Head (m)	Operator	Completion date
Kannagawa	2820	653	TEPCO	2015
Kazunogawa II	1600 (800 MW + option to expand)	700	TEPCO	NA
Omarugawa	1200	646	KEPC	2011

'pump-back' facilities is that energy storage is generally much greater thus allowing plants to store large amounts of cheap electricity. Plants with significant hydro inflow may also operate as conventional hydroelectric generation units during times of excess inflow thus increasing the economic competitiveness of the plant.

Repowering or enhancement of existing projects is also attractive as large savings are made on the capital expenditure of the project by using existing infrastructure, usually reservoirs thus also reducing environmental and planning issues. Repowered plants benefit from improvements in technology and design and usually use more efficient and larger turbines/pumps. From an investor standpoint the internal rate of return for repower project is on average higher than new plants [30].

Developers of new PHES in the review region tend to have diverse generating portfolios usually with significant amounts of wind capacity. This is particularly true in Europe.

6. Conclusion

This review papers details and presents over 7000 MW of new and proposed PHES in Europe, Japan and the USA with a total proposed investment cost of approx €6.7 billion. The majority of new plants are proposed in Europe. While there is considerable commercial interest in the USA, only one PHES plant has submitted a final environmental impact statement to the regulating authorities. Japan will continue to grow its PHES capacity over the next number of years but the available exploitable resource for economically viable PHES is dropping.

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